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Observing the first galaxies — a case for an intermediate resolution multi-object IR spectrograph

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Abstract. We present a special science case for an intermediate resolution multi-object IR spectrograph for the VLT. We have constructed new models for massive Population III stars and metal-free stellar populations (see Schaerer 2001). The properties of individual stars and integrated populations, including their ionising fluxes and SEDs are discussed. We also study their dependence on the poorly known IMF and the star formation history. The synthetic spectra are used to simulate spectroscopic observations of the expected emission lines of Pop III galaxies. We show that such an instrument should allow the detection and efficient observations of the first galaxies with the VLT.

1 Introduction

Important advances have been made in recent years on the modeling of the first stars and galaxies forming out of pristine matter — so called Pop III objects — in the early Universe (cf. review of Loeb & Barkana 2001, proceedings of Weiss et al. 2000 and Umemura & Susa 2001). With no doubt these efforts are motivated by the approaching possibility of direct observations of such objects at very high redshift with NGST and large ground-based telescopes.

What are the expected observational signatures of Pop III galaxies ? Tumlinson & Shull (2000, hereafter TS00) have recently pointed out the exceptionally strong He^{+} ionising flux of massive ($M \gtrsim 40$ M$_\odot$) Pop III stars, which must be a natural consequence of their compactness, i.e. high effective temperatures, and non-LTE effects in their atmospheres increasing the flux in the ionising continua. As a consequence strong He II recombination lines such as He II λ1640 or He II λ4686 are expected; together with AGN a rather unique feature of metal-free stellar populations, as discussed by TS00 and Tumlinson et al. (2001, hereafter TGS01). Instead of assuming a "standard" Population I like Salpeter IMF up to 100 M$_\odot$ as TS00, Bromm et al. (2001, hereafter BKL01) have considered stars with masses larger than 300 M$_\odot$, which may form according to some recent hydrodynamical models. An even stronger ionising flux and stronger H and He II emission lines were found.

Some strong simplifying assumptions are, however, made in the calculations of TS00, TGS01, and BKL01.

1) All stars are assumed to be on the zero age main sequence, i.e. stellar evolution proceeding generally to cooler temperatures is neglected (but cf. TGS01 for a simple estimate of this effect).
2) BKL01 take the hardness of the stellar spectrum of the hottest (1000 $M_\odot$) star as representative for all stars with masses down to 300 $M_\odot$. This leads in particular to an overestimate of the He II recombination line luminosities.
3) None of the studies include nebular continuous emission, which cannot be neglected for metal-poor objects with such strong ionising fluxes. This process increases significantly the total continuum flux at wavelengths redward of Lyman-α and leads in turn to reduced emission line equivalent widths.
4) A single, fixed, IMF is considered only by both groups. In view of the uncertainties on this quantity it appears useful to explore a wider range of IMFs.

We here present results from new calculations which relax all the above assumptions and allow the exploration of a wide parameter space in terms of stellar tracks (including also alternate tracks with strong mass loss), IMF, and star formation history (instantaneous bursts or constant SFR). A more detailed account is given in Schaerer (2001). The models are then used to simulate observations with a medium resolution cryogenic IR spectrograph for the VLT.

2 Input physics and results for individual stars

To account for non-LTE effects, which are crucial for a proper description of the spectra of hot stars considered here we use the *TLUSTY* code of Hubeny & Lanz (1995). Several additional models were calculated with the *CMFGEN* code of Hillier & Miller (1998) to explore the possible importance of mass loss (as well known for Pop I stars, Schaerer & de Koter 1997) on the ionising spectra of Pop III stars. For the hottest stars ($T_{\rm eff} \gtrsim$ 80 kK) dominating especially the ionising spectrum in the He II continuum, no significant differences with plane parallel models are found as their continua are formed deep in the quasi static part of the atmosphere.

We use stellar tracks from 1 to 500 $M_\odot$ calculated with the Geneva stellar evolution code (Desjacques 2000) or tracks from Marigo et al. (2001). Although probably unrealistic, we also explore the impact of high mass loss tracks from Klapp (1983) and El Eid et al. (1983). The atmosphere models and tracks are included in the synthesis code of Schaerer & Vacca (1998), which also calculates nebular line and continuous emission (adapted here to include additional lines and for an appropriate electron temperature $T_e = 30000$ K).

Based on these models we have calculated the ionising properties of ZAMS stars and their time averaged properties taking into account their evolution. The quantities are tabulated and given as fit formulae of use for various calculations (see Schaerer 2001).

3 Properties of Pop III "galaxies"

Integrated spectra have been calculated for a variety of IMFs. SEDs of integrated zero metallicity stellar populations are shown in Fig. 1 for the case of a Salpeter

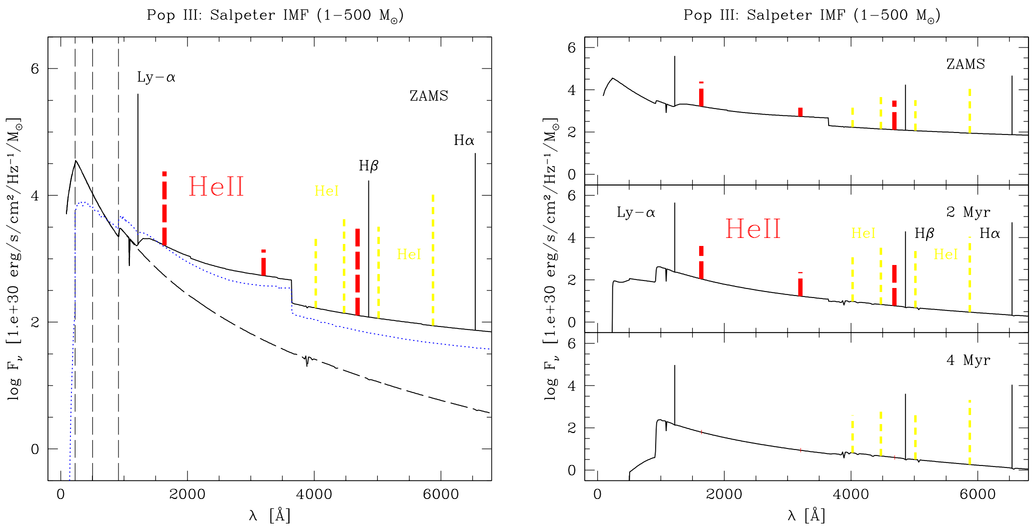

Fig. 1. Spectral energy distribution (SED) including H and He recombination lines for Salpeter IMF from 1 to 500 $M_\odot$. **Left panel:** ZAMS population. The pure stellar continuum (neglecting nebular emission) is shown by the dashed line. For comparison the SED of the $Z = 1/50 Z_\odot$ population (Salpeter IMF from 1 – 150 $M_\odot$) is shown by the dotted line. The vertical dashed lines indicate the ionisation potentials of H, He^0, and He^+. Note the presence of the unique He II features (shown as thick dashed lines) and the importance of nebular continuous emission. **Right panel:** temporal evolution of the spectrum for 0, 2 and 4 Myr showing the rapid change of the emission line spectrum, characterised by the disappearance of the He II lines

IMF from 1 to 500 $M_\odot$ and instantaneous bursts of ages 0 (ZAMS), 2, and 4 Myr. Overplotted on the continuum (including stellar + nebular emission: solid lines) are the strongest emission lines for illustration purpose. The striking differences when compared with non-zero metallicity, most importantly in the ionising flux above the He II edge (> 54 eV), have already been discussed by TS00. The comparison of the total spectrum (solid line) with the pure stellar emission (dashed) illustrates the importance of nebular continuous emission neglected in earlier studies (TS00, BKL01), which dominates the ZAMS spectrum at $\lambda \gtrsim 1400$ Å. The nebular contribution, whose emission is proportional to $Q(\mathrm{H})$, depends rather strongly on the age, IMF, and star formation history. For the parameter space explored (see Schaerer 2001), we find that nebular continuous emission is not negligible for bursts with ages $\lesssim$ 2 Myr and for constant star formation models.

The spectra in Fig. 1 show in addition to the H and He I recombination lines the presence of the strong He II $\lambda\lambda$ 1640, 3203, and 4686 recombination lines, which — due to the exceptional hardness of the ionising spectrum — represent a unique feature of Pop III starbursts compared to metal enriched populations (cf. TGS01, Oh et al. 2001, BKL01). Another effect highlighted by this Figure is the rapid temporal evolution of the recombination line spectrum. Indeed, already

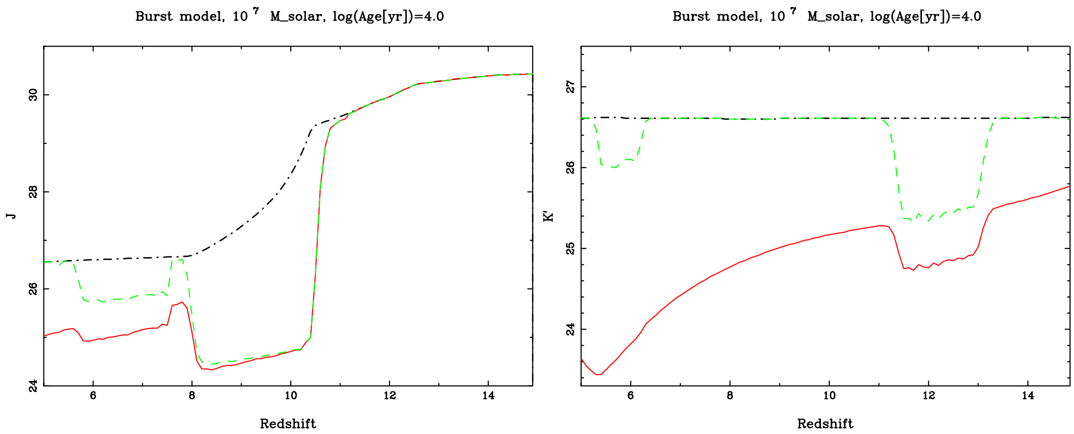

Fig. 2. J (left) and K′ (right) band magnitude as a function of redshift over the interval $z \sim 6$ to 14.5. Pure stellar continuum: upper dashed-dotted curve; intermediate/green dashed curve: including the Lyman-α, He II λ1640, and He II λ3203 emission lines; total predicted spectrum including lines and nebular continuous emission (lower curve/red). Note the increase by $\sim 1 - 2.5$ mag depending on z!

$\gtrsim$ 3 Myr after the burst, the high excitation lines are absent, for the reasons discussed before.

The detailed behaviour of the relative line intensities and equivalent widths and their dependence on the IMF and the star formation history are discussed in Schaerer (2001). For the case of constant star formation, the He II or H recombination lines can be used as a measure of the star formation rate (SFR). For obvious reasons, strong variations of the various SFR indicators on the poorly known IMF are obtained.

4 Simulations for a 2nd generation multi-object IR spectrograph on the VLT

We have used the above synthetic spectra to calculate the photometric properties and to simulate spectroscopic observations. The following assumptions are made: A popular cosmology ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 75$ km/s/Mpc^{-1}) is adopted. Lyman-α forest blanketing at redshift $z < 6$ is included following the prescription of Madau (1995). Sources are unresolved on a 0.3" scale, and the seeing adopted is 0.8". We take typical SOFI and ISAAC near-IR filter responses to calculate magnitudes in the Vega system. Telescope parameters correspond to the VLT. The characteristics of the near-IR spectrograph are set similar to EMIR (Balcells et al. 2000), with 0.3"/pixel, 1" slit-width, and a mean total efficiency of 40%. All simulations shown here are calculated for a ZAMS population of 10^7 M$_\odot$ with a Salpeter IMF from 1 to 500 M$_\odot$ (somewhat more "favourable" than a constant star formation case), a total exposure time of 10^5 sec, and resolutions $R \sim 1000$ to 5000.

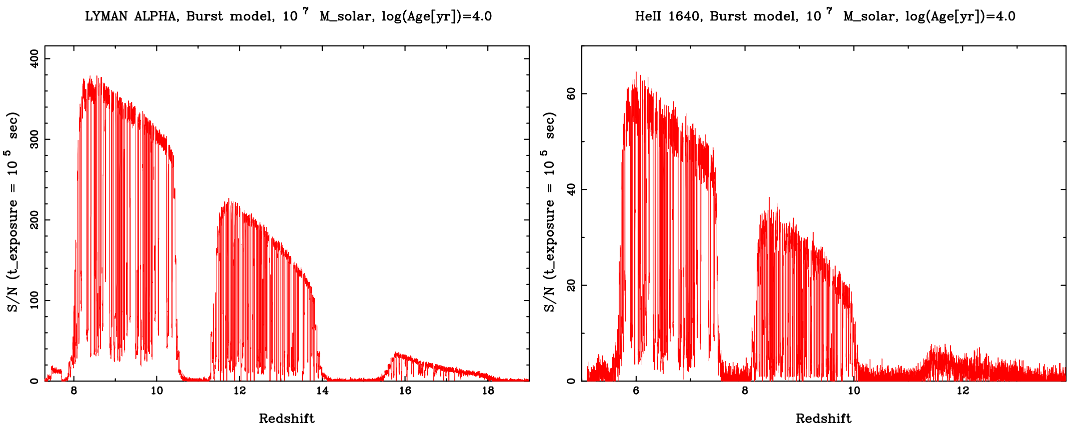

Fig. 3. Predicted S/N in Lyman-α (left) and He II $\lambda1640$ (right) as a function z for a spectral resolution $R = 1000$ and $t_{\rm exp} = 10^5$ s, for a 10^7 $M_\odot$ burst at age ~ 0 with a Salpeter IMF from 1 to 500 $M_\odot$

As shown in Fig. 2 the predicted magnitude in the K′ band is $\sim 24 - 25$ for a 10^7 $M_\odot$ burst. This Fig. shows also the strong contribution of the nebular continuum, and the signatures of the strong emission lines on this broad band filter, which both need to be taken into account. Similar effects are observed in the other filter bands, the most relevant emission lines being Lyman-α and He II $\lambda1640$. Simulations for various cases of the IMF show that standard broad-band colors do not allow a distinction between upper mass cut-offs of 100 to 1000 $M_\odot$ and are also insensitive to changes of $M_{\rm low}$.

The expected S/N in Lyman-α and He II $\lambda1640$ as a function of redshift of the source (observed in the JHK bands) for a spectral resolution of 1000 is plotted in Fig. 3. The calculations illustrate the following:

- Lyman-α can easily be detected with a good S/N over a redshift ranges ($z \sim$ 8–10.5, 11.5–14, and 15.5–18). A joint detection with He II $\lambda1640$ is possible for $z \sim 5.5$–7.5 (Lyman-α in optical domain) and $z \sim 8$–10; at larger redshift the S/N of He II $\lambda1640$ becomes very low.
  A detection of both He II $\lambda1640$ and Lyman-α is obviously important to secure the redshift, and to obtain a measure of the hardness of the ionising flux. This allows potentially the distinction between different IMFs.
- Higher spectral resolution ($R \sim 5000$) considerably increases the chances of detection between the sky lines. For unresolved lines the resulting decrease of S/N is modest. The medium spectral resolution is also required to attempt to measure the emission line profiles, in order to distinguish Pop III source from AGN (cf. TGS01). Once this is obtained, the data can be rebinned to increase the S/N.

How many such Pop III galaxies are expected ? The number of metal-free objects depends of course on the galaxy formation scenario, the star formation efficiency, and the hydrodynamical enrichment process of the ISM, among other factors. The comprehensive study of Ciardi et al. (2000) shows that at $z \gtrsim 8$ naked stellar clusters, i.e. objects which have complete blown out their ISM dominate the population of luminous objects. One may expect that all metals are ejected in this way into the IGM, thereby avoiding largely local pollution, i.e. leaving these objects as Pop III "galaxies". Based on such an assumption and using the ionising fluxes from TS00, Oh et al. (2001) have recently calculated the predicted number of Pop III starbursts detectable in He II lines with NGST for a one day integration. Their estimate yields between ~ 40 and 3000 sources in a 8'x8' field of view envisaged for the proposed IR multi object spectrograph. Although pilot studies have recently started to explore the formation of dust in Pop III objects (Todini & Ferrara 2001), the effect is neglected here.

In conclusion, a medium resolution (R up to ~ 5000) IR multi-object spectrograph on the VLT covering the J, H, and K band would not only be of great interest to numerous studies of intermediate and high-redshift galaxies (cf. contributions of Cuby, Genzel, Lefèvre, this meeting). It should also allow observations of the first so called Pop III objects — certainly one the great remaining challenges of observational astronomy. If realised on a reasonable time scale, such ground-based observations with the VLT at ESO should be able to achieve an important breakthrough before the launch of NGST.

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